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This manuscript will be submitted to the Journal of Geophysics

for publicaton and the contents are subject to change

MEASUREMENT OF SALINE ICE THICKNESS USING A STEP FREQUENCY RADAR

by

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ABSTRACT

The Step Frequency Radar as a means of determining the thickness of saline ice was tested and evaluated under various conditions of salinity of ice, height of the antennas above the ice surface, and homogeneity of the ice sample.

Measurements were made with salinities of 2.5, 4.0, and 5.5‰. The thickness of the ice was changed at 12 cm intervals up to 70 cm. The attenuation of the radar signal per unit thickness of 5.5% saline ice was 22.7 dB/m.

RÉSUMÉ

On a fait l'essai du radar à fréquence en échelon pour la détermination de l'épaisseur de la glace saline et évalué son rendement en fonction de divers paramètres : salinité de la glace, hauteur des antennes au-dessus de la surface de la glace et homogénéité de la glace.

Des mesures ont été faites à salinité de 2,5 ‰, 4,0 ‰ et 5,5 ‰, et à des épaisseurs de glace augmentant par incrément de 12 cm jusqu'à 70 cm. L'atténuation du signal radar dans de la glace saline à 5,5 ‰ d'épaisseur unité était de 22,7 dB/m.

I. INTRODUCTION

There is a need for an instrument to remotely detect discontinuities in an electrically lossy medium such as the measurement of ice thickness for Arctic navigation, and the determination of depth and location of plastic gas and water pipes. These applications require high resolution, and consequently a high operating frequency. A high frequency, on the other hand, means increased attenuation in the lossy media. Thus, a criterion exists in maximizing resolution and minimizing the operating frequency.

In order to circumvent the above conflicting requirements, the Step Frequency Radar was proposed[1]. The basic principle of this radar was the utilization of real-time Fast Fourier Transform (FFT) to process the phase and amplitude of target-reflected signals.

In order to test the radar under controlled conditions and because the laboratory grown saline ice and first year sea ice are similar[2],[3], it was decided to test the radar using artificial sea ice. To determine the capability of the radar to operate under field conditions, the radar was tested under various parametric conditions of different salinities of ice, different heights of the antennas above the ice surface and different homogeneity of the ice .

II. PRINCIPLE OF THE STEP FREQUENCY RADAR

When a continuous radio wave is reflected from an object, the phase shift of the reflected signal relative to the transmitted signal is proportional to the distance travelled by the reflected signal.

Let

$$E = E_0 e^{j\omega t} \tag{1}$$

be the transmitted signal, where ω is the angular frequency. The reflected signal from a single target will be

$$H = KE_0 S e^{j(2\beta d - \omega t)} \tag{2}$$

where K is a factor associated with attenuation, S is the back scattering cross-section of the target, β is the propagation constant, and d is the distance between the radar and the target. Thus, by measuring the phase βd in Eqn. (2), for a given β, the value of d can be determined.

In the case where there is more than one target, the measured phase is the superposition of the reflected signals from all targets. This resultant signal does not allow for the determination of the individual distances. However, this difficulty can be circumvented by using a stepped frequency signal and processing the received signal with FFT.

When N targets exist, each having a separation distance of d_n, the plot of the real and imaginary components of the received signal with respect to β is the superposition of N sinusoidal curves with each having a period of $\left(\frac{\pi}{d_n}\right)$. The FFT can identify each sinusoidal waveform and hence enable the identification of the various target distances.

The algorithm used by the Step Frequency Radar to identify the various separation distances is as follows. The frequency of the

transmitting signal is shifted in discrete steps. At each frequency during this shifting process, the phase and amplitude of the received signals are recorded. The received signal at the nth frequency is the sum of the scattered signals from all targets.

$$H_n = KE_0 \sum_{k=0}^{N-1} S_k \, e^{j4\pi \left(\frac{f_0 + n\Delta f}{v}\right) k\Delta y} \tag{3}$$

Where N is the number of frequency steps, S_k is the scattering coefficient of the kth target, f_0 is the starting frequency, Δf is the frequency increment, v is the velocity of the propagating wave in the medium, $k\Delta y$ is the quantized distance to the kth target, and the time factor $e^{-j\omega t}$ is suppressed.

Equation (3) is rearranged to the following format for ease of mathematical operation

$$H_n = \sum_{k=0}^{N-1} h_k \, e^{j2\pi \frac{kn}{N} \frac{2\Delta f N}{v} \Delta y} \tag{4}$$

where

$$h_k = KE_0 S_k e^{j4\pi \frac{f_0}{v} k\Delta y} \tag{5}$$

If the following condition is imposed

$$\frac{2\Delta f N}{v} \Delta y = 1 \tag{6}$$

then equation (4) can be regarded as the inverse DFT of h_k. This allows the values of h_k to be determined from the FFT of H_n, and consequently, S_k to be determined from h_k by Eqn. (5). It should be noted, that

Eqn. (6) specifies the relationship of resolution in terms of the number and size of frequency steps.

III. EXPERIMENTAL ARRANGEMENT

To facilitate quick change in the thickness of an ice sample, to minimize the handling weight and the time required to freeze the sample, six ice blocks measuring 84 x 84 x 10 cm^3 were frozen in wood frames lined with plastic sheets. The sea water was simulated by mixing aquarium sea water salt (Forty Fathoms Biocrystal Marine Mix, Marine Enterprises Ltd) with tap water. The salinity was monitored with a salinity meter and measured by weight. After pouring the saline solution into the wood frames, it was left in a walk-in refrigerator to freeze over a period of 5 days at a temperature of -18°C.

For the testing of the radar, the six ice blocks and frames were stacked on top of each other. Plywood strips, 1 cm thick, were placed along two edges of each frame; thus permitting an 82 cm wide aluminum sheet to be inserted beneath any of the layers. This aluminum sheet simulated the ice saline water interface which was acceptable because the reflection coefficient of the ice saline water interface was greater than 0.7, and thus can be considered as a perfect reflector. The above arrangement permitted fast ice thickness changes from one to six ice blocks by inserting the aluminum sheet at the desired level.

The experimental set up is shown in Figs.1 and 2. The blocks of ice were stacked up on a UHF absorber to prevent radio wave reflections from the floor.

The radar was first calibrated with a known ice thickness.

The first experiments were conducted with the radar antennas placed directly on the ice surface. For the subsequent experiments the antennas were raised to various heights, up to 89 cm, above the ice surface.

IV. EXPERIMENTAL RESULTS

IV-A Location of the Reference Plane

The first experiment was conducted to test the influence of the calibration thickness. Each test consisted of thickness measurements for six different thicknesses at 12 cm intervals. The results of the first test with the salinity of the ice at 2.5‰ and a calibration ice thickness of 35 cm, were plotted in Fig.3. The curves represent the scattering intensity of six thickness measurements. It should be noted that the curves were normalized to the peak scattering intensity from the thinnest ice thickness. Similar tests were carried out with calibration ice thicknesses of 24 cm and 48 cm These tests were conducted with two other ice salinities of 4.0‰ and 5.5‰.

In all tests, the results were similar. It was found that the location of the scattering intensity peaks corresponded to the actual thickness of the ice, with the exception of thin ice for which the measured thickness was greater than the actual thickness of the sample. This could be attributed to the shallow angle of illumination.

The error introduced by the shallow angle of illumination can be explained using Fig.4. The thickness of the ice was measured from a

reference plane as established in the calibration of the radar. The position between a measured plane, P_2, and a reference plane, P_3, as seen by the radar was the signal path difference.

$$\overline{TP_3R} - \overline{TP_2R} = 2d\cos\theta \tag{7}$$

Thus, for a θ other than 0°, the determined thickness of the sample will be greater than the actual thickness. This problem will not be significant until θ becomes large. For example, an error of 10% will be introduced with a θ of 25.8°. If needed, this problem can be easily rectified during the processing of the data.

IV-B Dependence on Ice Salinity

Experimental tests were performed with ice samples of differing salinity. The thickness measurements obtained with ice samples having salinities of 2.5‰, 4.0‰, and 5.5‰ were similar. Therefore, the determination of a sample thickness was unaffected by the salinity of the sample.

The electrical properties of saline ice were determined by a method of field-probe.[4] The result[5] was that the simulated saline ice had a dielectric constant of 6 at the radar's mid-frequency of 500 MHz.

An approximate expression that relates the power of the received signal, P, with the signal path distance, d, is

$$P(d) = \frac{P_0}{4d^2} e^{-2\alpha d} \tag{8}$$

The ratio of the received powers from d_1 and d_2 thick ice samples gives

$$10 \log_{10}\left(\frac{d_1^2 P(d_1)}{d_2^2 P(d_2)}\right) = 20 \alpha(d_2-d_1)\log_{10}e \tag{9}$$

Thus, the attenuation in decibel per metre is

$$A = \frac{10 \log_{10}\left(\frac{d_1^2 P(d_1)}{d_2^2 P(d_2)}\right)}{d_2-d_1} = 8.686\alpha \text{ dB/m} \tag{10}$$

The values of A and α were determined by plotting the numerator versus the denominator of Eqn. (10) as is shown in Fig.5.

The propagation constant is related to the loss tangent by

$$\tan\delta = \frac{2\frac{\alpha}{\beta}}{1-\left(\frac{\alpha}{\beta}\right)^2} \tag{11}$$

The loss tangent is further related to the imaginary component of the complex dielectric constant by

$$\varepsilon'' = \varepsilon' \tan\delta \tag{12}$$

where

$$\varepsilon = \varepsilon' - j\varepsilon'' \tag{13}$$

The parameters as determined from the experimental results using Eqns. (10) through (12) are tabulated in Table 1. The results indicate that a change from 2.5‰ to 4‰ in salinity causes a 10.8 dB/m increase in signal attenuation.

TABLE 1: Electrical Properties of Saline Ice

Salinity (‰)	A (dB/m)	α (n/m)	tanδ	ε'	ε''
2.5	9.4	1.09	0.085	6	0.51
4.0	20.2	2.33	0.18	6	1.05
5.5	22.7	2.61	0.20	6	1.2

The Step Frequency Radar has an approximate dynamic range of 50 dB. The attenuation per unit thickness of saline ice was 22.7 dB/m for an ice salinity of 5.5‰. Thus, the Step Frequency Radar would be capable of penetrating and determining the thickness of 2 metres of saline ice of salinity 5.5‰.

Throughout the experimental test, the half power width of the scattering intensity was within 10 cm. To detect the thickness of saline ice, the resolution of the radar can be approximately stated as 10 cm.

IV-C Inhomogeneity in the Ice

The influence of ice inhomogeneity on the radar's performance was investigated. In the first case, saline water was introduced as a contaminate to the homogeneity of the sample. In the sixth layer, approximately 80% of the saline solution was solidified, leaving the remaining 20% of the saline solution at the bottom of the container. In the fifth layer, a few patches of saline solution existed at the bottom of the container. The results of the introduced contaminate, as shown in Fig.6, where the scattering intensity peaks corresponding to the fifth

and sixth layers. These peaks were shifted and attenuated unlike the homogeneous case shown in Fig.3.

These shifts allow the depth of the saline water to be calculated. Assuming that the dielectric constant of saline water was 80 and that of saline ice was 6, then the calculated saline water content of the fifth and sixth layer were 4% and 17% ,respectively. These results roughly confirmed the visual inspection of the experimental set-up.

In continuing the investigation of the influence of impurities in the tested sample on the radar's performance, a 35 cm air void was placed between the 3rd and 4th layers. The height of this air void corresponded to a wavelength ratio of $0.58\lambda_a$ and $1.47\lambda_i$, where λ_a and λ_i were the mid-frequency wavelength in air and ice, respectively. The salinity of the ice was 4‰. The size of the air void as registered by the radar, as shown in Fig.7, was 17 cm. The dielectric constant of the hosting medium, including the air void, was assumed to be 6. In reality, the dielectric constant of the air void was 1, and thus the location of the scattering intensity was shifted by a factor of $\sqrt{6}$. Taking into account this factor, the physical dimension of the air void as determined by the radar was 42 cm which was 7 cm greater than the actual dimension.

IV-D Off Surface Operation

The mobility and manoeuvreability of an ice radar would be significantly increased if the system could be raised above the ice surface.

Several problems, however, are expected with off surface operation. These problems originate from

1. Mismatch of the input impedance of the antennas.
2. Reflection at the air/ice interface.
3. Increase in mutual coupling between the antennas.

4. The change in the radiation pattern of the antennas.

Though each individual effect was not studied, the resultant effect was observed by operating the antennas at various heights above the ice surface. In comparing the radar's performance with the antennas raised 89 cm above the ice surface as shown in Fig.8 and the radar's performance using the same ice sample of salinity 2.5‰ but with the antennas directly on the surface as shown in Fig.3, it was found that the dynamic range of the radar had been reduced by operating the antennas off the ice surface. Despite this reduction, the radar's ability to determine the thickness of the saline ice was not hindered by off surface operation.

Similar measurement results, were obtained by operating with an ice sample having a salinity of 4‰. The signal to noise ratio was increased as the antennas were off the ice surface especially when the salinity was high and the ice was thick.

To observe the effects of raising the antennas, the scattering intensity curves at a specific thickness were plotted for the antennas operated at 0 cm, 54 cm, and 89 cm above the ice surface. This comparison was performed for ice samples having a salinity of 2.5‰ and 4.0‰ and a thickness of 24 cm and 48 cm. Fig.9 shows the result of the 4.0‰ salinity experiment. It was noticed that certain measurements, such as the case of 4‰ salinity, 48 cm thick ice and with an antenna to surface separation of 54 cm exhibited a higher noise level than most of the others.

V. CONCLUSIONS

Experiments were performed using laboratory grown saline ice of

differing salinities to test the performance of a Step Frequency Radar as a device to measure the thickness of saline ice.

The tests showed that the radar was capable of penetrating and detecting the thickness of up to 70 cm of laboratory grown saline ice of salinity 5.5‰. Taking into account the dynamic range of the radar, 50 dB, it is predicted that the radar would be capable of penetrating and detecting the thickness of up to 2 m of saline ice.

Also, it was demonstrated that the radar could operate from a height of 89 cm above the ice surface. Such information will be useful in the development of an off-surface radar.

Throughout the test, the resolution of the radar was found to be 10 cm.

VI. ACKNOWLEDGEMENTS

The authors wish to express their appreciation to Mr. E.O. Lewis of the Department of Fisheries and Oceans for his enthusiastic support to this project. Experimental facilities were provided by the Hydraulics Division, National Water Research Institute.

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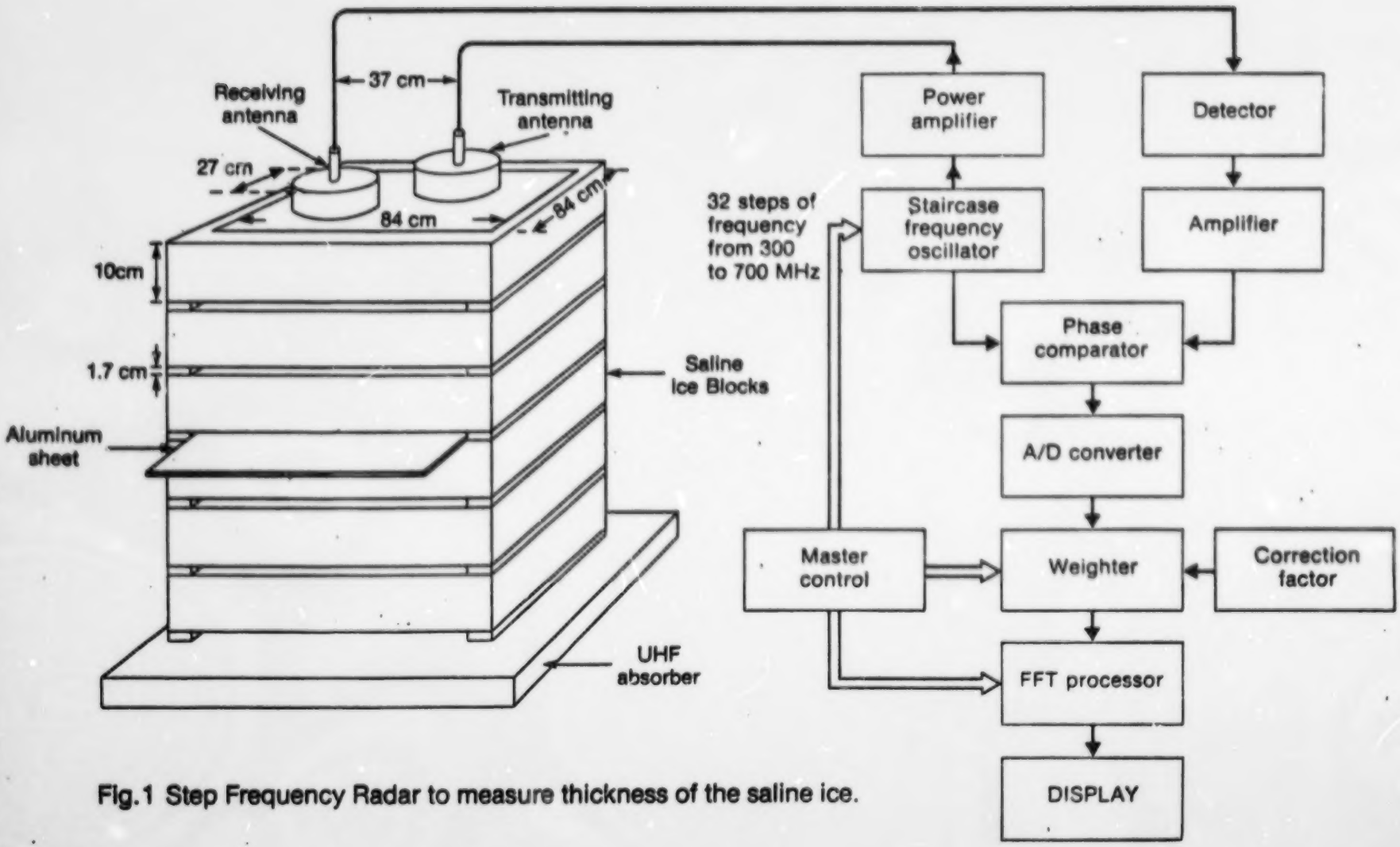


Fig.1 Step Frequency Radar to measure thickness of the saline ice.

Fig.2 A photograph of experimental arrangement to measure the thickness of saline ice.

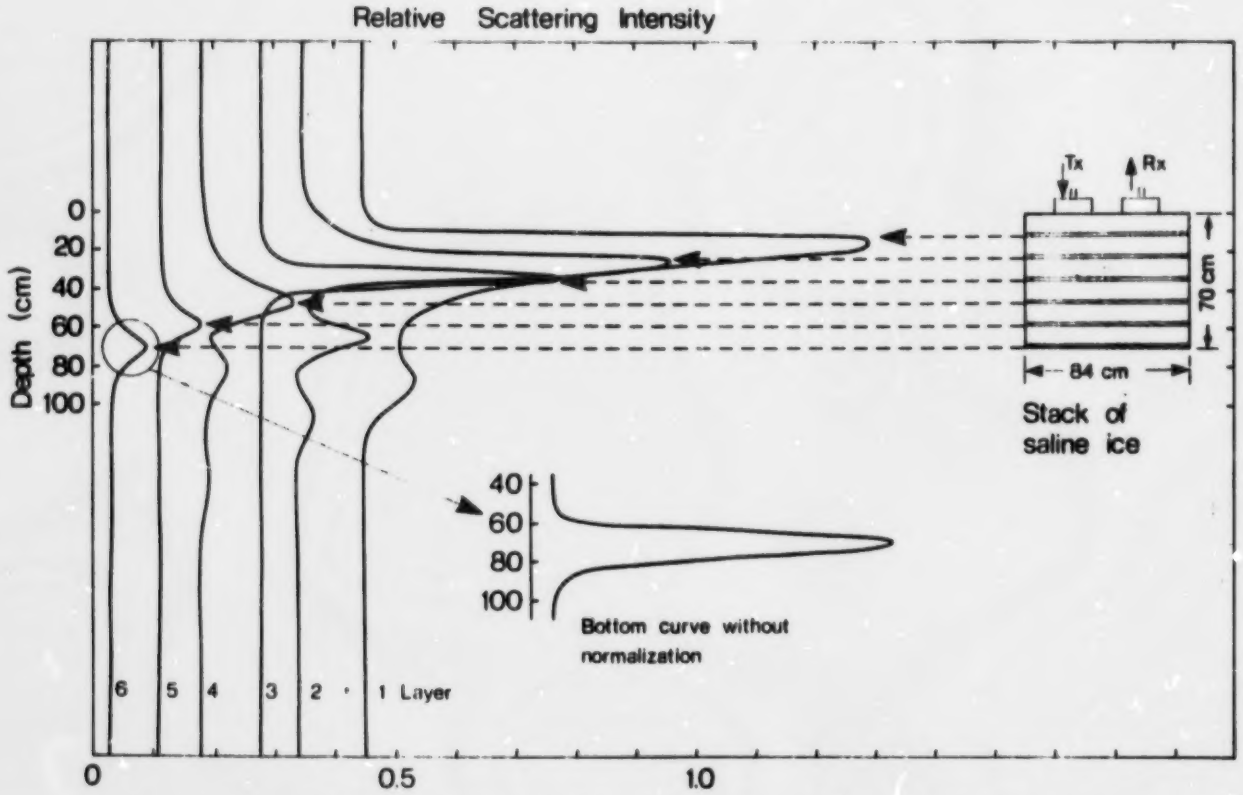


Figure 3: Relative scattering intensity for various ice thicknesses.
Salinity of ice: 2.5 ‰ Location of reference plane: 3rd layer

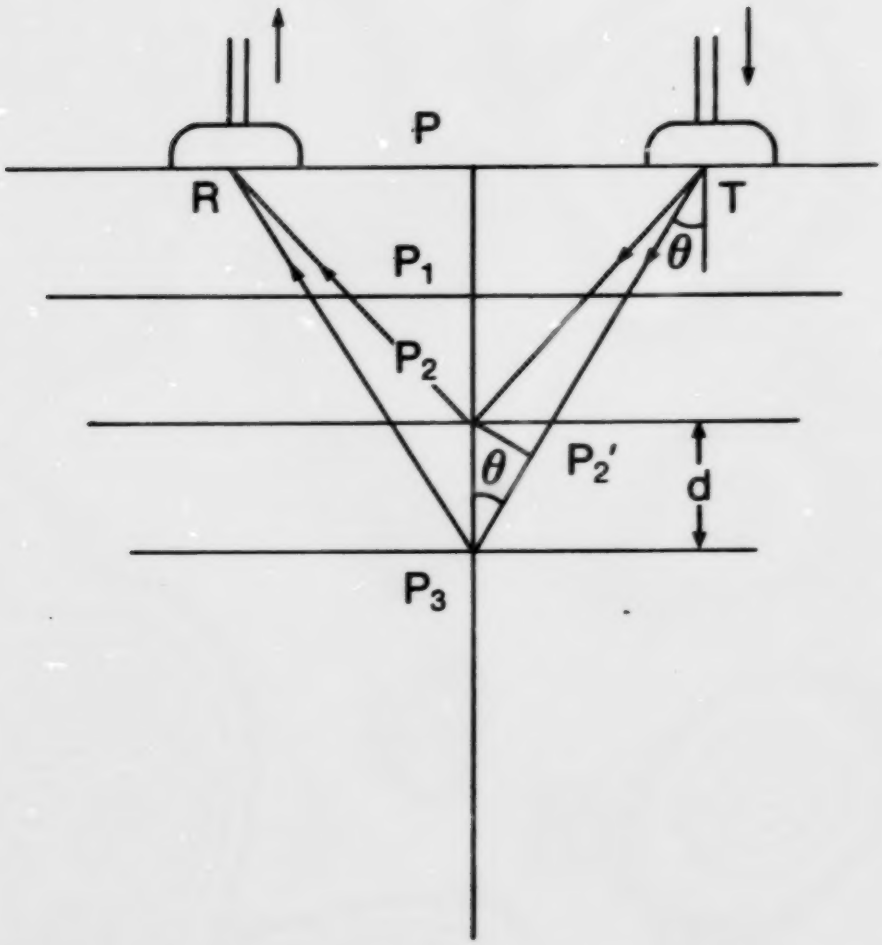
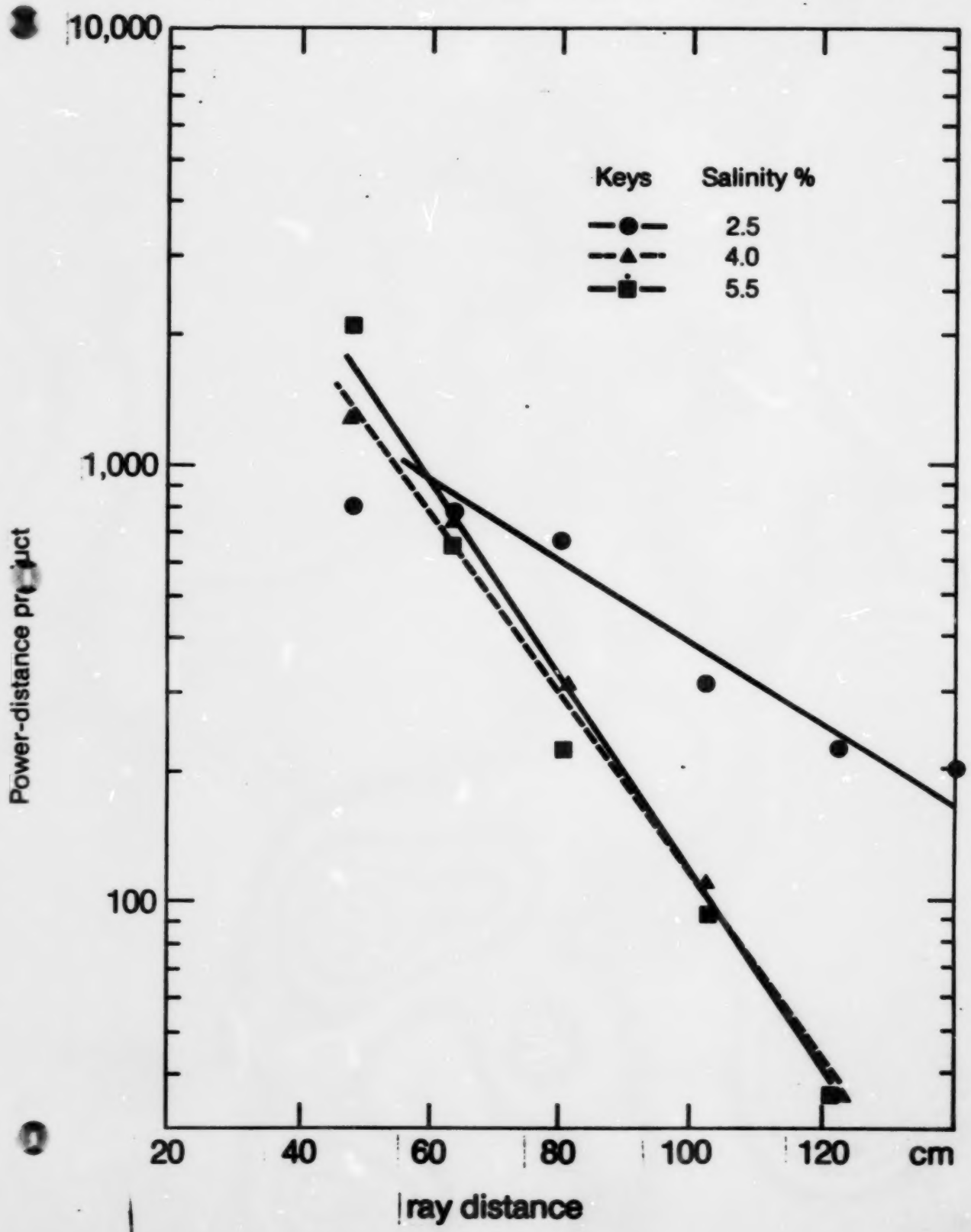


Fig. 4 Geometry of a ray reflecting from a shallow layer.

Fig. 5 Power distance product vs distance for determining attenuation constant.



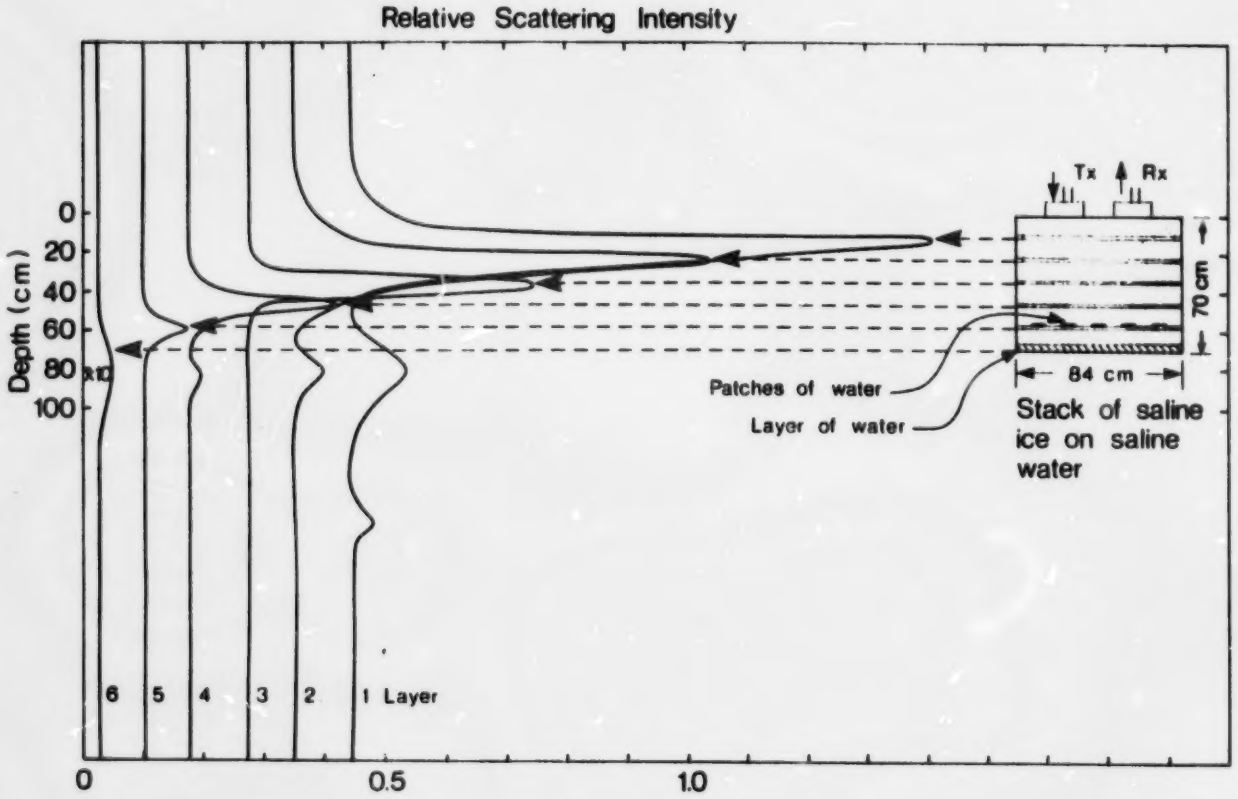


Figure 6: Relative scattering intensity for various thicknesses of inhomogeneous ice. Salinity of ice: 2.5‰

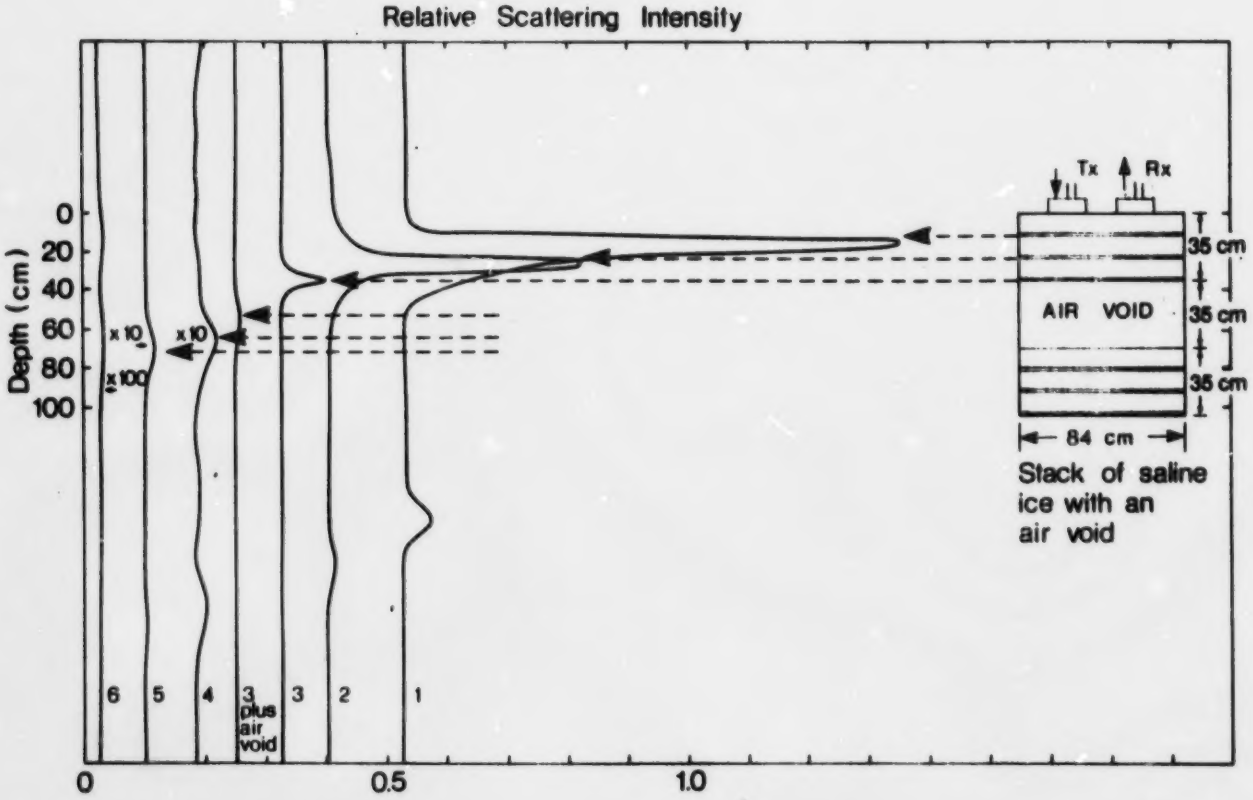


Figure 7: Experimental results with inhomogeneous ice. Inhomogeneity was introduced by 35 cm air void. Salinity of ice: 4.0‰

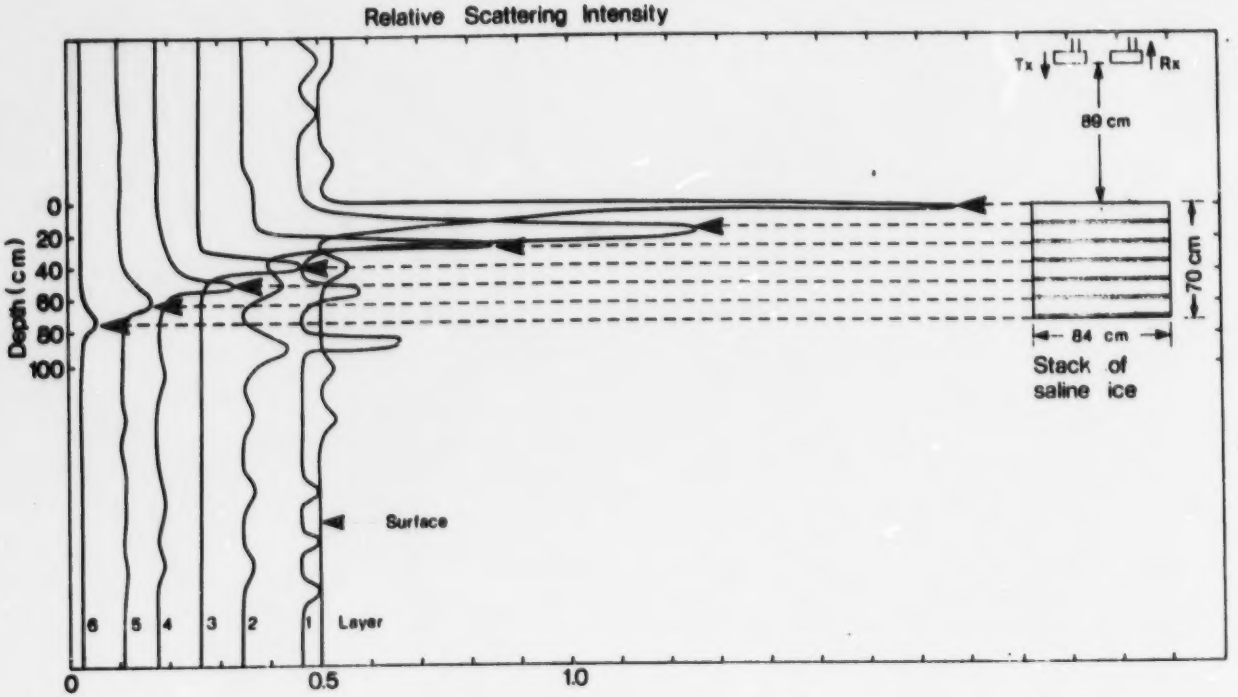


Figure 8: Relative scattering intensity for various ice thicknesses with the antennas operating 89 cm above the ice's surface. Salinity of ice: 2.5‰

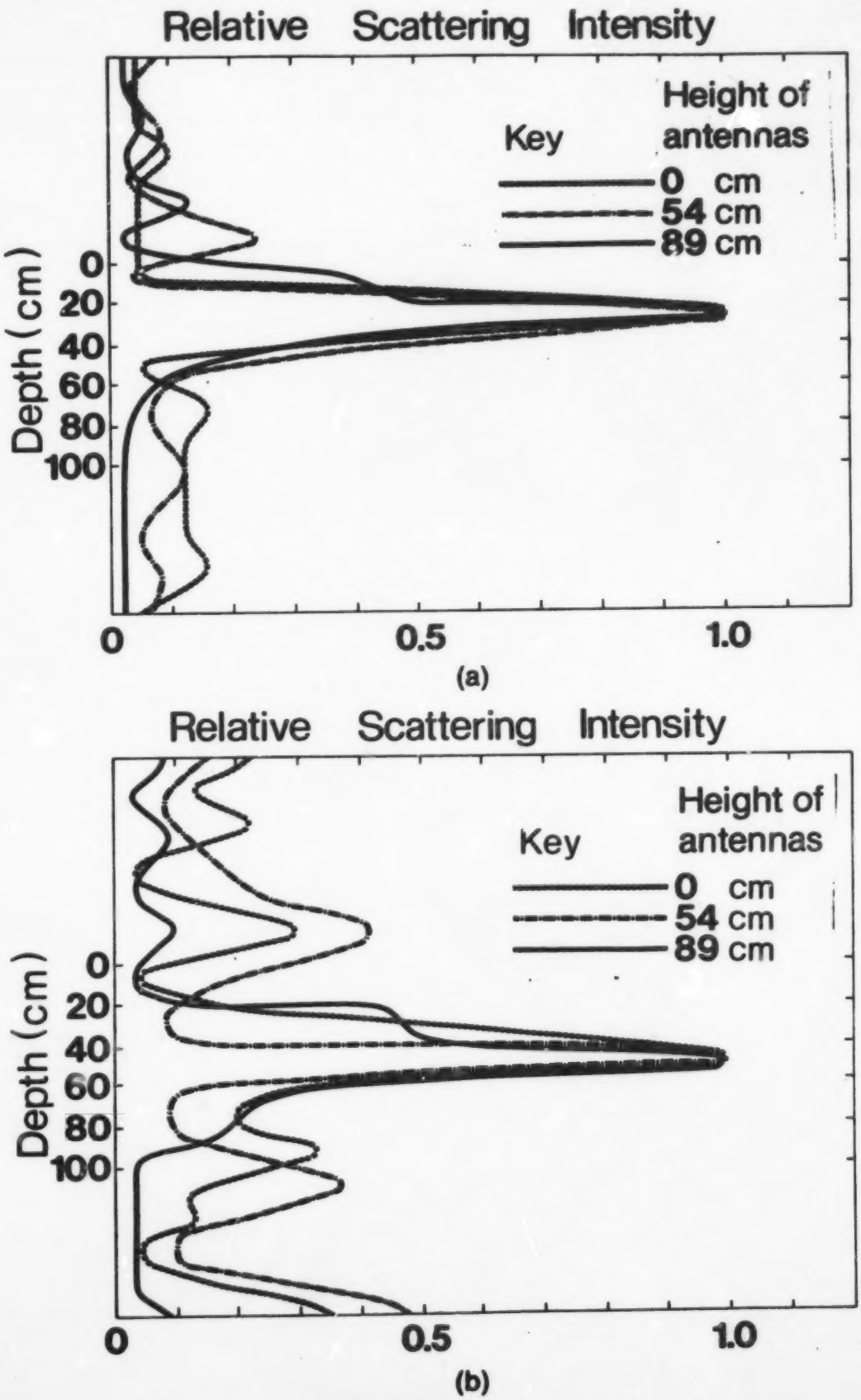


Figure 9: Relative scattering intensity for a specific ice thickness with the antennas operating at various heights above the ice's surface. Salinity of ice: 4.0‰ (a) 24 cm thick ice, (b) 48 cm thick ice